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Optimization Aspects of the ARAC Real-Time Radiological Emergency Response System

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Abstract

The Atmospheric Release Advisory Capability (ARAC) project at the Lawrence Livermore National Laboratory responds to radiological emergencies throughout the Continental United States. Using complex three-dimensional dispersion models to account for the effects of complex meteorology and regional terrain, ARAC simulates the release of radioactive materials and provides dispersion, deposition, and dose calculations that are displayed over local geographic features for use by authorities at the accident/release site. ARAC's response is ensured by a software system that (1) makes optimal use of dispersion models, (2) minimizes the time required to provide projections, and (3) maximizes the fault-tolerance of the system. In this paper we describe ARAC's goals and functionality and the costs associated with its development and use. Specifically, we address optimizations in ARAC notifications, meteorological data collection, the determination of site- and problem-specific parameters, the generation of site-specific topography and geography, the running of models, and the distribution of ARAC products. We also discuss the backup features employed to ensure ARAC's ability to respond.

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Introduction

Many scientists believe that complex atmospheric transport and dispersion models cannot be used for real-time assessments of radiological releases. The time required to collect meteorological observations and source-term information, for example, can make the consistent provision of reliable projections difficult in a time frame useful for emergency response. However, the goal of the Atmospheric Release Advisory Capability (ARAC) project at the Lawrence Livermore National Laboratory has been to develop an optimized emergency response system utilizing complex dispersion models in real time. The key emphasis in achieving that goal has been to optimize three things: the quality of the projection, the time required for calculations, and the fault-tolerance of the system to compensate for hardware/software failure in order to guarantee a response.

Background

In 1972 the United States Department of Energy's predecessor, the Atomic Energy Commission, realized that its response to nuclear accidents could be improved substantially by developing a capability for real-time assessment of the transport and dispersion of radioactivity released into the atmosphere. They envisioned that such a capability, when integrated with various radiation measurement systems, could help emergency response personnel improve their real-time assessments of the potential consequences of an accident. That vision led to Lawrence Livermore National Laboratory's development of ARAC. This capability uses advanced three-dimensional atmospheric transport models to simulate the release of pollutants into regional-scale flow systems and to prepare projections for dissemination to local accident response officials.

The objective of the ARAC project as designed in 1973 was to provide real-time predictions of the dose levels and extent of surface contamination from accidental releases of radioactive materials. The first computer system used for this purpose was a prototype designed to determine the feasibility of using complex dispersion models for emergency response. By definition, simple models have eliminated much, if not most, of the complexity associated with the atmospheric dispersion of material and, as a consequence, are easy to compute. For the purpose of evaluating individual basic processes under (unrealistic) steady state conditions, such models can be both relevant and insightful. However, actual transport and dispersion processes can be highly complex in the everchanging (spatial and temporal) regime of the lower atmosphere. Thus, to provide a more accurate assessment during accident conditions, it is necessary to model as many of the major diverse atmospheric processes as possible. For effective real-time response, however, a limit must be drawn when results cannot be calculated and delivered within a practical time frame of 15 to 45 minutes.

The prototype system not only proved the feasibility of preparing projections using complex models for emergency response, but has been used operationally for more than 125 real-time events and exercises. For example, it was used for the Three Mile Island nuclear power plant accident, the COSMOS satellite reentries, and the TITAN II missile accident. Since then, increasing commitments by the Departments of Energy (DOE) and Defense (DOD), combined with aging hardware and software, have provided the impetus for a complete redesign and upgrade of the existing ARAC system. This redesign, which has been underway for the past two and one-half years, is being funded jointly by the DOE and DOD and should meet our current goals by the end of 1986. As of June 1985, about 80% of the prototype hardware and software had been replaced by the new system, which is designed to take advantage of lessons learned in using the prototype system and in first-hand experience with accident site personnel during actual emergency responses.

Project Goals

The ARAC project's overall goal of improving the effectiveness of emergency response was broken into specific goals of developing a computer system whose projections are viable for use in real-time situations and of staffing the project with meteorologists who can do quality assessments. Attempts to satisfy these goals led to certain specifications for the new ARAC system. Namely, it has to:

- Produce quality assessments using complex dispersion models.
- Have preliminary calculations using a unit-normalized source term available within 15 minutes after notification.
- Produce sophisticated calculations within 45 minutes of notification and every hour thereafter until the release terminates and any hazard to people has passed.
- Support up to 100 remote sites with site computer systems.
- Respond rapidly to accidents at arbitrary locations where no site computer system is available.
- Ensure the system's ability to respond through backups in hardware, software, meteorological data sources, and delivery capability for projection results.
- Support a 24-hour/day staff of highly trained emergency response personnel.
- Handle up to three emergencies simultaneously within the specified time frame of hourly projections.

System Configuration and Functionality

The ARAC emergency response operating system incorporates computers at the central facility in Livermore, site computers at ARAC-supported sites across the Continental United States, and microprocessors on ARAC meteorological towers at the same supported sites [1].

System Hardware Configuration

The basic hardware configuration (Fig. 1) at the central facility consists of two Digital Equipment Corporation (DEC) VAX 11/782 computers that use three DEC LSI 11/23 computers as communications front-end processors. DEC PC350 computers and meteorological towers with Handar 540 microprocessors are used as the site system at ARAC-supported facilities. A Xerox 495 telecopier connected to the VAX computers will allow the central facility to transmit VAX-produced graphics directly from the VAX to remote telecopiers at both supported and nonsupported sites. A voice-synthesized page/alarm system with microprocessor is used to alert emergency response personnel.

System Functionality

Users at the ARAC central facility can initiate a response using an on-line questionnaire for entry of source-term information, collect meteorological data, simulate releases using complex dispersion models that account for the effects of local terrain, prepare graphical displays of all projections overlaying the local geography, and distribute these projections to on-site authorities (see Fig. 2).

Site computer users can initiate a response at the central facility by entering source-term information into an on-line questionnaire. They can also use the system to collect meteorological data from on-site towers, enter on-line supplementary meteorological observations obtained from local (sometimes portable) instruments, provide two-way communication with the central facility, prepare simple dispersion model calculations, and graphically display both these models and complex projections prepared at the central facility.

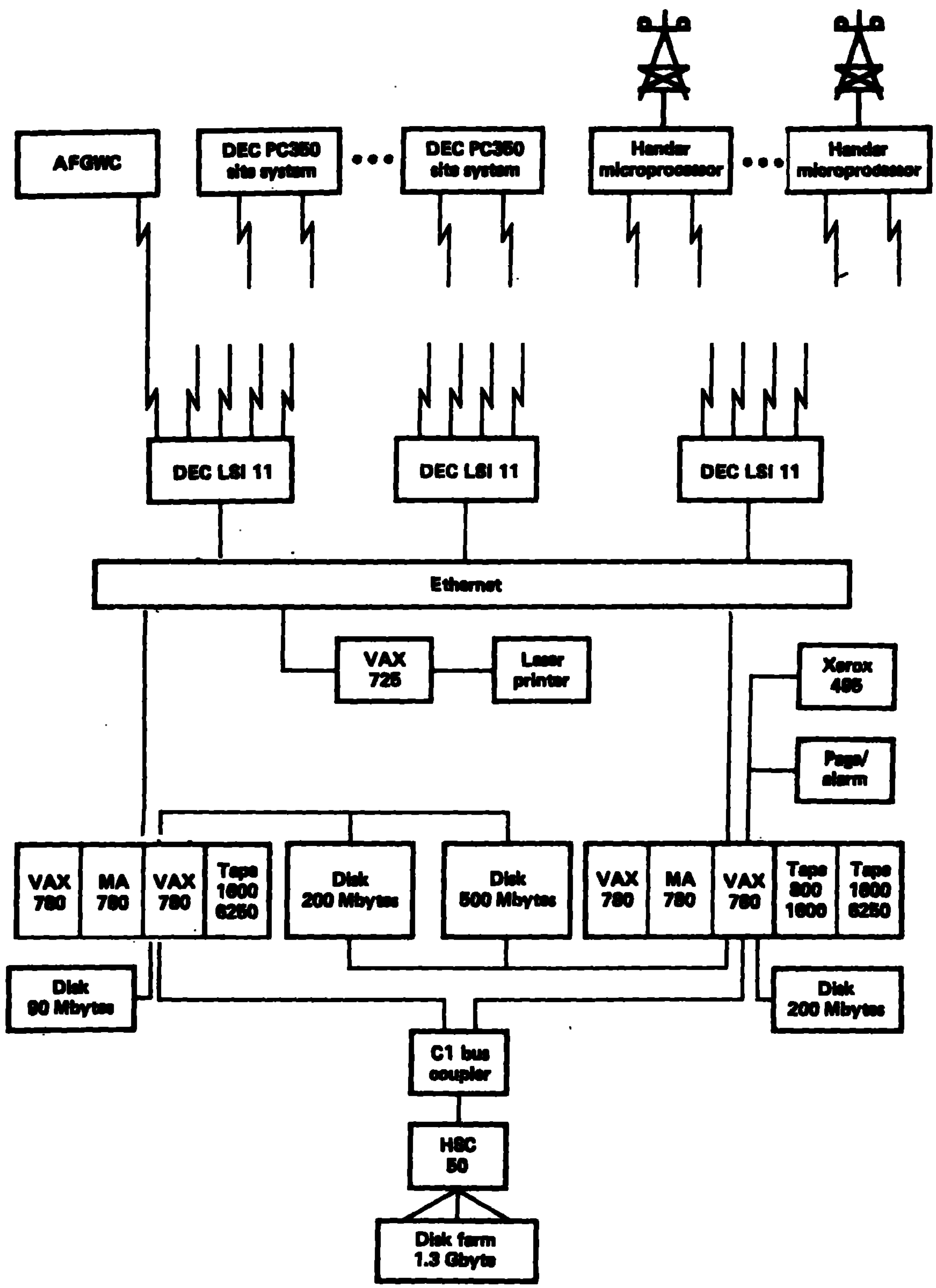

Figure 1. ARAC hardware configuration.

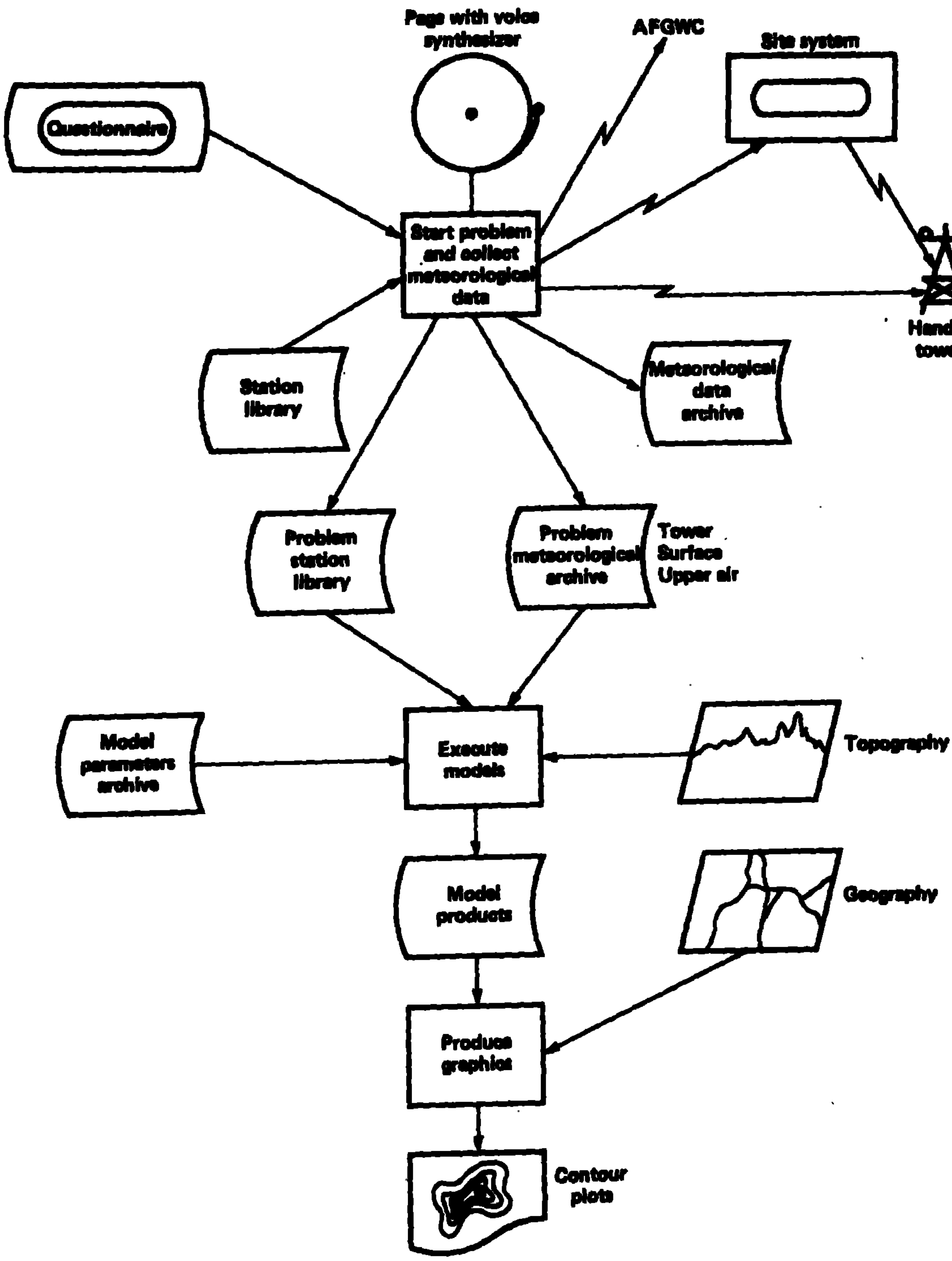

Figure 2. Diagram of ARAC emergency response system.

ARAC microprocessor-based meteorological towers are used to collect and archive meteorological observations continuously. These towers are accessible for collection of observations by both the site computer system and the ARAC central computer system.

A communications system manages the transfer of messages and files between the ARAC central computers and the individual site computers. This system requests and receives worldwide meteorological data from the United States Air Force Global Weather Central (AFGWC). It can also obtain meteorological data from the site meteorological towers by means of the site-system computers.

Quality Optimizations

To provide quality assessments, ARAC provides quality-assured inputs, model calculations, and graphical displays of the resulting projections. Model inputs consist of meteorological data and corresponding station information, site- and problem-specific model parameters, and site-specific topography.

Inputs

Meteorological Data Collection

Meteorological data for the location and duration of a release are collected in real time for input to the models. Most world meteorological data for these models come from the AFGWC, which provides a worldwide master station catalog of all stations that report meteorological data. A default radius for the accident/release site is used to select appropriate surface and upper-air stations for calculations. All observations—from the start of the release to the current time—for the corresponding stations are requested from the AFGWC.

Within two minutes, ARAC can request, receive, and decode meteorological observations for anywhere in the world. Noncurrent data that are less than 48 hours old can be retrieved in 5 to 10 minutes. For stations in the vicinity of a supported site, we also maintain a subscription service with the AFGWC to supply ARAC with those observations continuously. By archiving the subscription data, we can, upon notification, instantly begin calculations for supported sites. Archiving also provides some backup capability should the AFGWC link fail or should we need to respond to releases that occurred more than 48 hours earlier at supported sites.

ARAC's station library also contains locations of ARAC site towers, which are often deployed at supported sites along with the site system. This allows radius calculations to select ARAC tower stations in the vicinity of the accident release site and to request those observations from the corresponding site system. Site-tower observations are used to supplement meteorological data received from the AFGWC. These data are available for use on the site system and at the central facility. Supplementary observations from local (sometimes portable) instruments are also used. These supplementary observations can be entered through either the site or central system. For hourly calculations, the system typically collects the necessary meteorological data by 20 minutes after the hour.

Model Parameters

We are developing user aids to help the assessment meteorologist determine model parameters. These aids will offer the meteorologist a choice of algorithms for computing parameter values, default values (some of which are site-specific), automatically computed values, on-line databases, and on-line help information.

Problem-specific information, such as the location and time of the release, the substances involved, and whether the release is in the form of a puff or a plume is entered into an on-line questionnaire at the central facility or on a site system. This information is accessible by the computer models.

For supported sites, site-specific maps are displayed in the questionnaire. To specify the release coordinates, the user positions a cursor at the location of the release. The software then uses the cursor position to determine the release coordinates. Site maps are also used for interactive selection of the model calculation grid.

Model parameter values (such as boundary/mixing layer depth, stability class as determined by sigma–theta and delta–T methods, Monin–Obukhov length, wind-profile power-law exponents, and atmospheric thermal structure) will be estimated automatically in software on the basis of available meteorological and questionnaire information. Plume rise as a function of input thermal energy and explosion cloud geometries as a function of the amount of explosive material will also be estimated automatically. The meteorologist can modify these values interactively by choosing recalculations based on a choice of algorithms, by specifying the use of default values, or by inputting values directly. Default values, as well as values used for the preceding hourly calculation, will be displayed for reference.

On-line databases will archive information needed to speed model calculations. Information about potential accident/release sites, such as probable accident location, type of terrain, station-specific Pasquill–Turner stability, and local area surface roughness, is stored on line. Data on dose-conversion factors and half-lives for various radionuclides and exposure pathways are also stored on line for interactive use and for automated processing by software that converts air concentration and ground deposition to radioactive dose. On-line information to document procedures, aid in decision-making, and help the meteorologist interact with the system is available throughout the system.

Site-Specific Topography

A digital terrain database from the United States Geological Survey (USGS) supports the topography portion of the system for the Continental United States [2]. The Defense Mapping Agency has also provided terrain data for portions of Europe. In addition, we are developing a contour-to-grid capability that will allow us to digitize terrain from contour maps. Within three minutes, we can extract (for model input) local topography at 500-meter resolution for any area in our terrain database. If an area is not in our database, we can assume flat terrain, enter the terrain elevations manually, or, in the future, digitize a contour map.

Model Projections

From its inception, ARAC has been dedicated to the application of state-of-the-art calculational models to fulfill real-time emergency response needs. At present, this means detailed treatment of flow that is three-dimensional, terrain-influenced, vertically sheared and/or stratified, and spatially and temporally varying with three-dimensionally varying diffusion. These models are in a continuous state of evolution and advancement.

ARAC uses many simulation models. The two used most often for assessment are $MATHEW_2$ [3] and $ADPIC_3$ [4]. MATHEW uses surface, tower, and upper-air wind data to develop an initial, three-dimensional, mass-consistent wind field that includes the effects of topography. Using this wind field, the ADPIC model (a three-dimensional, particle-in-cell transport and diffusion code) can calculate the time-dependent dispersion and deposition of radioactive pollutants. Real-time assessments are run hourly and contain calculations of individual dose and of instantaneous and time-integrated concentrations. Population dose can also be provided on a post-accident basis.

To verify the models, a number of studies and experiments have been conducted to compare projection calculations against measured results [5–7].

Graphical Displays

Model projections are in the form of numerical results, as well as device-independent graphics. The model-prepared graphics for use by local officials consist of plots showing the contours of varying pollutant concentrations overlaying the local geography (Fig. 3). Other graphics products can be generated to aid meteorologists at the ARAC central facility.

A digital line-graph database containing geographic features will support the ARAC geography system. The geography data are divided into separate overlays for water bodies, rivers, streams, roads, railroads, political boundaries, etc. ARAC is in the process of building the database and developing a system to extract local geography for anywhere in the Continental United States. Meanwhile, we are using a digitizing system to generate base maps for supported sites. In the future, this digitizing system will only be used to generate maps that are not in the database or to add detail to a map generated from the digital database (Fig. 4). Local authorities use such maps to orient the contour plots with respect to local landmarks.

Graphics products are distributed to authorities at supported sites by means of the site-system computers. When sites are not supported or the site system is down, these products are distributed by telecopier. Site systems can also do simple model calculations and display the results graphically. These graphical displays include a simple Gaussian diffusion model with contours of concentration that can be updated regularly with current data from the local site tower. The site system can also generate tower profiles, upper-air profiles, or wind roses.

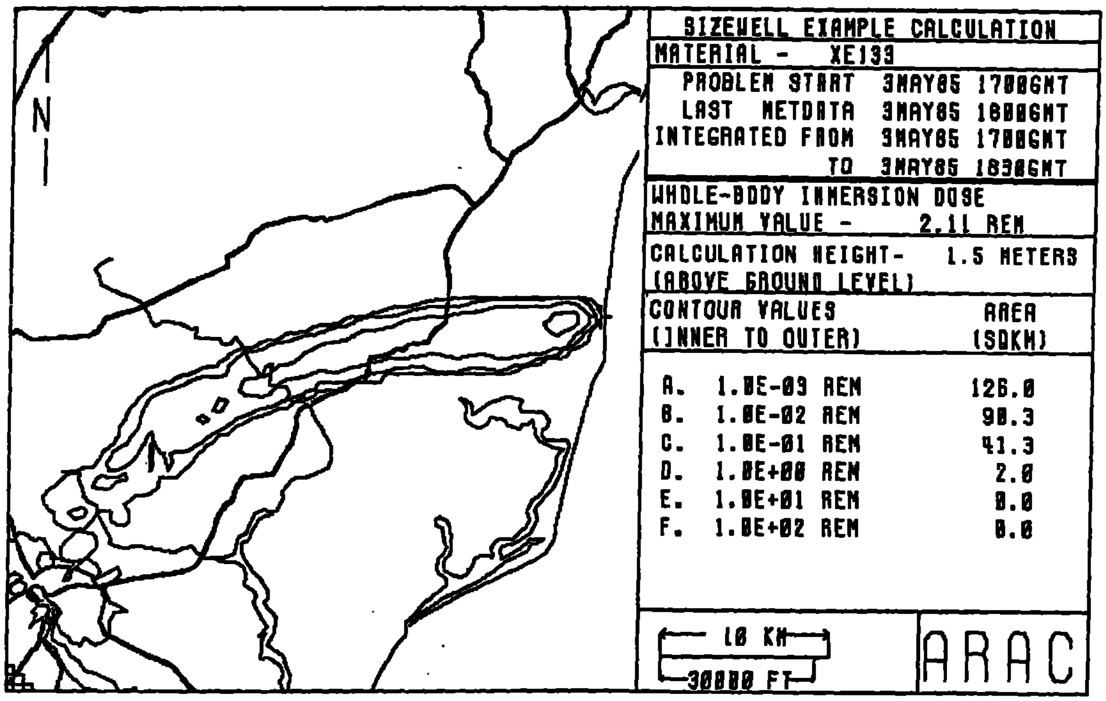

Figure 3. Typical graphics plot.

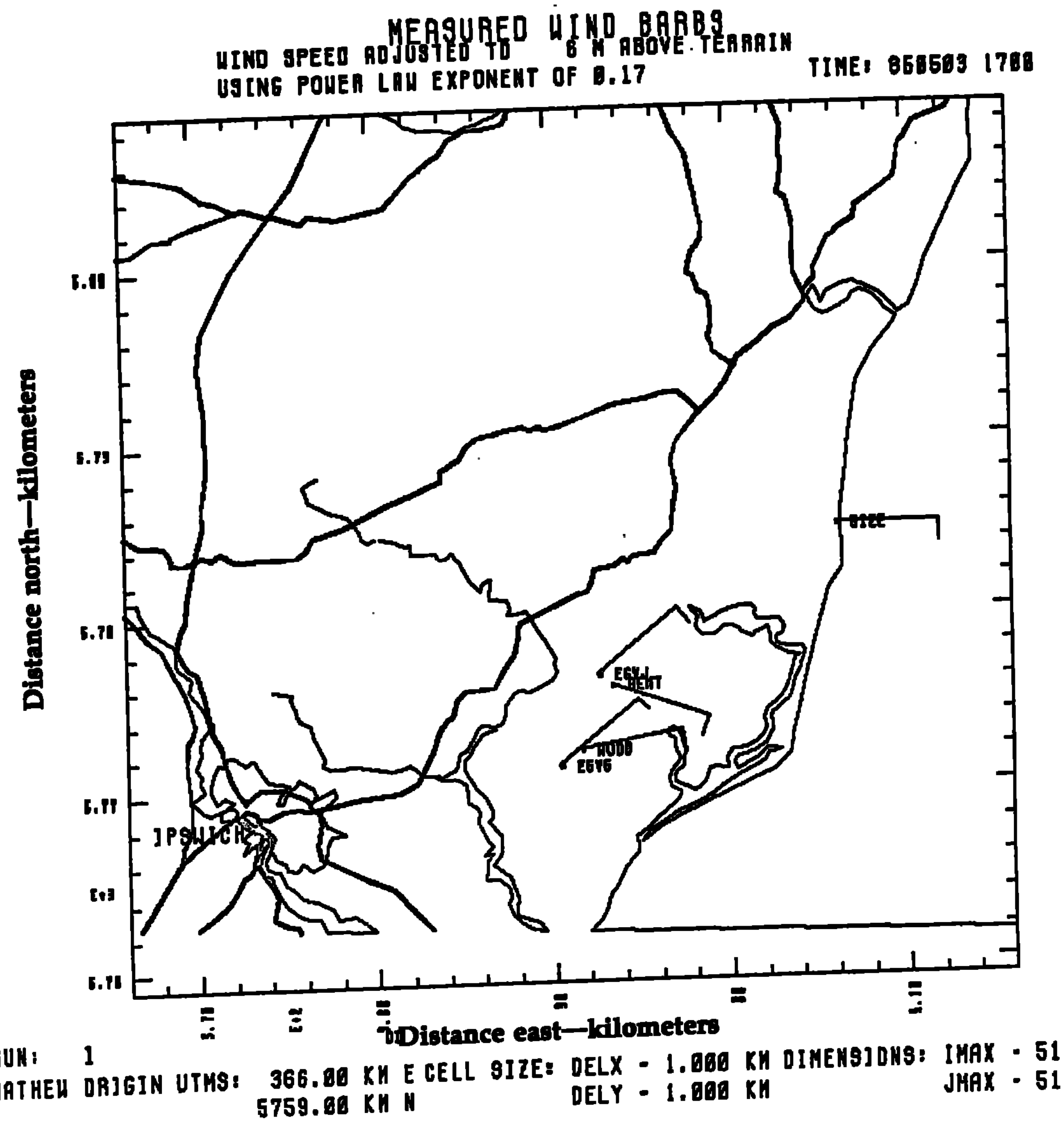

Figure 4. Map generated from digital database.

Timing Optimizations

Our efforts to optimize response time have been focused on making the best use of the meteorologist's time. This subject has been addressed by automating notification of ARAC, automating data collection, reducing sytem dependence on human action, focusing human intervention on quality assurance, and considering human engineering factors.

Automated Notification of ARAC

All exercise or emergency responses are initiated by filling out an on-line questionnaire. This questionnaire can be completed by local authorities using a site system or by a meteorologist at the ARAC central facility, who may receive the information by telephone.

Responses to the questionnaire are sent immediately to the ARAC central system. As soon as the central system receives notification, a microprocessor-based emergency page/alarm system with voice synthesizer alerts ARAC personnel.

Automated Data Collection

The system has been built with numerous automated capabilities that are initiated by the software as soon as the corresponding information is entered in the questionnaire. As soon as the release time is recorded on the questionnaire, automated station selection and meteorological data collection are initiated for stations in the default radius of the release. Observations for the selected sites are requested automatically from the appropriate meteorological data source. This request includes all observations issued by those stations since the time of the release. The automated data collector continues to request these observations, at default intervals, until the meteorologist indicates to the system that the problem is terminated.

Another process monitors the receipt of requested meteorological data. Unfilled requests are reissued automatically. If a primary data source is down, requests are reissued automatically to the appropriate alternate meteorological data source. Meteorological observations, including subscription observations, are automatically decoded and archived.

When the new system is complete and determines that sufficient meteorological data have been received, it will automatically run a preliminary dispersion and deposition calculation using the ARAC models with flat terrain. Site-specific model parameters are archived on line for supported sites. Default or estimated values will be used in the initial calculation for nonsupported sites. This initial calculation will be used at ARAC and by on-site authorities as the first indicator of the nature and severity of the problem.

Site topography and geography for supported sites are available on line. For nonsupported sites, the new system will automatically build a terrain grid from existing databases. At present, the geography for nonsupported sites must be digitized on line, but the initial projection for a nonsupported site usually contains no base map. To remedy this, we are developing a capability that will allow us to build the geography base maps from existing databases as we do now for the topography.

All of the above actions can occur automatically before the meteorologist or site user has completed the questionnaire. As soon as the meteorologist has reviewed and released the model graphics products, the site system is notified that they are available.

Reduction of Human Dependence

During an assessment, the meteorologist must be free to concentrate on the problem and to consult with authorities at the accident/release site. Thus, for optimum use of the meteorologist's time, we have reduced the system's dependence on human actions and interactions. While the automation of data collection processes has eliminated much of the need for human action, the meteorologist can, by means of interactive interfaces to the automated processes, intervene or change automatically selected default values, stations, and other input.

Human Intervention and Quality Assurance

To save time and increase confidence in the calculations, human intervention is focused on quality assurance. All meteorological data are automatically validated to flag both questionable and fatal input values. Upper-air profiles supply information on winds in the upper levels of the atmosphere. Meteorological data history plots for all stations used for a problem enable the meteorologist to determine the reasonableness of the observations. A three-dimensional terrain graphics display is currently under development [8].

To notify the meteorologist of hardware and software problems, we have built extensive error-detection into the system. Error messages generated by the site system are formatted into operator messages and sent to the central system. Interactive processes inform the meteorologist of errors. Automated processes also generate journal error messages. If a problem is severe, it is broadcast immediately to the meteorologist.

All information relating to a problem is archived to facilitate post-assessment studies. This includes the questionnaire, the model parameters used for the calculations, meteorological data, graphics products, operator and error messages, journals, and an automatically generated summary of response.

Human Engineering Factors

Human engineering factors (ergonomics) were also considered important ingredients in optimizing the use of time. In developing menus and forms for the site and central systems, we had to account for the expertise of the user, which, in the case of the site user and the ARAC user, differs radically. This divergence in expertise means that forms that could easily be understood by a novice site user are too tedious for the ARAC assessor staff. Therefore, we built forms that would lead the site user through data entry and other, more flexible forms, for ARAC personnel.

Fault-Tolerance Optimizations

Our efforts to optimize fault-tolerance have been directed toward identifying conditions under which the system could fail to calculate and deliver an assessment and to provide a backup capability to ensure our ability to respond. These efforts have identified failure modes in hardware, software, real-time meteorological data collection, product delivery, and communications.

Hardware

We have identified single points of hardware failure and, in most cases, provided redundant backups. One of the two VAX computer systems at the central facility is used for emergency response; the other is used for backup and software development. Either system can access the disk drives used for emergency response. For communications, the central facility has three LSI 11 computers available to both computers on ETHERNET.

Software

Software design includes consideration of recovery modes if portions of the software fail. For certain cases, we provide the ability to restart or retry and have designed the system so that it will not fail when expected records or files are not found. The system is also designed to notify the ARAC assessor immediately when a serious error occurs, even when the error occurs in an automated process, communications, or the site computer system. We have devoted considerable effort to software error detection and notification so that erroneous values can be corrected or eliminated.

Meteorological Data

We have identified backup sources for the collection of meterorological data. A local organization called WeatherNet can supply observations within the United States should the AFGWC or the communications link fail. If the site system computer fails, we can request observations directly from the site meteorological tower. In the event the tower fails, local users can read backup instruments directly and enter obsevations into the site computer or phone them into the ARAC central facility.

Product Delivery

The ARAC center transmits most graphical displays of calculated projections to the site system computer. If that link fails or the accident occurs at a nonsupported site, the telecopier can be used to transmit them. Two telecopiers are available to allow for telecopier breakdowns.

Communications

Because leased lines are prohibitively expensive, we use dial-up lines to communicate with the site computers. Unfortunately, there are numerous ways this communications link can fail. The phone line can be of poor quality, an established phone link can be lost, or busy circuits can make it difficult to establish a connection during a real emergency. To cope with some of these problems, we have built considerable retry logic into our communications software protocols. If an established link is lost, the software tries to reestablish the link automatically. Special phone numbers to supported sites improve the likelihood of establishing a link. We have also built in a concept of *lines open permanently* and *lines open temporarily*. Communications automatically establishes a link to the site (or from the site to the center) whenever there is a message or a file to be transmitted. When an emergency is declared, a permanent connection is established; it cannot be disconected, except by explicit operator commmand, until the problem is terminated. If an emergency has not been declared, a timer is used on the line; this timer causes the line to disconnect when no traffic has occurred for a default period of time.

Economics and Value of a Centralized Service

Economics

The economics (or cost and staffing) of a centralized facility must be evaluated in terms of the service performed and the number of facilities serviced. Approximately 52 person-years of effort (15 operations, 12 model development, and 25 systems development) were expended in developing the prototype system (1974–1978). A comparable 54 person-years (28 operations, 26 systems maintenance) were expended on an interim operations and enhancement phase (1979–1982). The replacement system (which began in 1983) has expended 86 person-years of effort (21 operations, 65 systems development) to date and will likely expend another 32 person-years (7 operations, 25 systems development) before completion in 1986. Operating costs for systems development and for maintaining an operational emergency response capability since 1974 are shown in Fig. 5(a). These costs include the costs for a seven-member (approximately) operations staff to maintain a 40-hour/week emergency response capability (with 72 hours maximum endurance). The ARAC operations staff is on call to cover releases that occur during nonscheduled shifts.

Capital equipment costs are depicted in Fig. 5(b). Note that there are two major equipment procurement periods—one associated with the prototype hardware (1976–1977) and one with the current expansion (1982–1985). There are also two physical facilities expansion phases associated with housing the staff and computer equipment.

As a single site entity, ARAC would be prohibitively expensive and difficult to cost-justify. At present, however, it provides an emergency response service (or capability) for ~50 sites at a cost of ~$4 million U.S. or ~$80,000 U.S./site at a service level of 40-hour/week (plus on-call). The present upgrade and expansion is designed to support ~100 sites at a cost of ~$50,000 U.S./site and to reduce a site's operational staff needs and initial investment in research and development. In addition to reducing the cost per site, ARAC

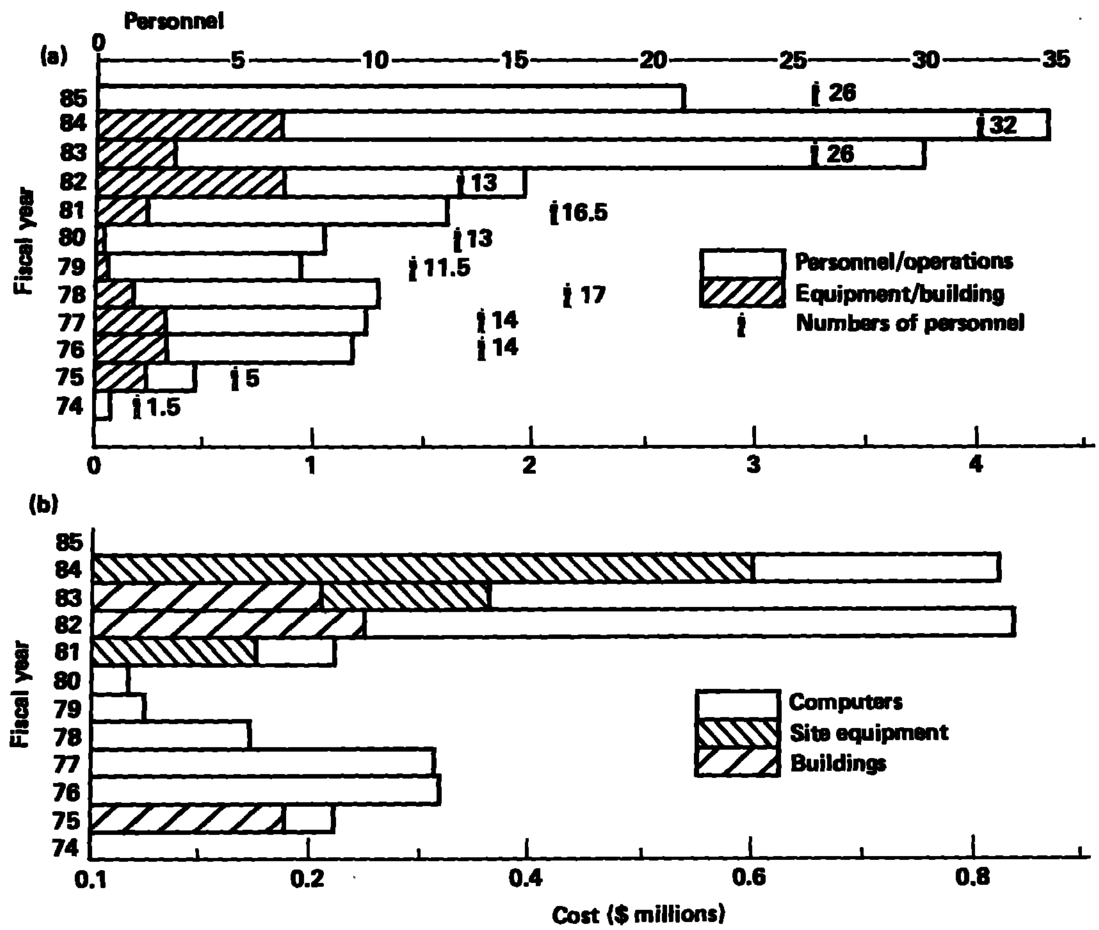

Figure 5. (a) Total ARAC funding and staffing and (b) equipment and building funds.

provides a response service that is superior to what a site could afford to develop for itself. Significantly greater than the quantifiable cost, however, is the value of the service, which cannot be measured in terms of dollars.

Value of Centralized Service

The value of a centralized service can be evaluated and discussed in the context of objectivity, quality, availability, adaptability, and information consistency.

Objectivity

Objectivity embodies detachment from emotional or psychological involvement, perhaps even bias. Because of ARAC's relative remoteness and organizational detachment from an accident/release site, it is easier for ARAC personnel to respond in a calm unbiased fashion. This detachment can also contribute to a broad view of the risks, liabilities, and vulnerabilities of the area around the accident site, not just the specific plant/facility. Such objectivity lends itself to thoroughness in an accident assessment.

Quality

The *quality* of an ARAC assessment or emergency response must be considered from the view that the state-of-the-art atmospheric and dispersion models employed in calculating projections are on the leading edge of technology for real-time response. A wealth of quality control procedures, computer software, and graphic aids have been developed and are continually exercised and evaluated by the operational staff. Finally, the staff has developed more diverse emergency response experience and expertise than any single site facility could possibly amass. The evolutionary improvements and accumulation of experience are prime contributors to the quality of the ARAC service.

Availability

ARAC is *available* for response at both supported sites and sites that have no other capability to produce dispersion projections. The inability to respond can occur at locations that are unprepared to respond, where local equipment fails, or when the local response center cannot be manned because of contamination or damage. Generally, no other capability exists to respond to transportation accidents or terrorist threats. Even when a local response capability exists, there is value in comparing the calculational results. Agreement instills confidence in the calculations. If they disagree radically, early detection of input errors will produce a more accurate assessment.

Adaptability

Another benefit of centralized service is the expertise acquired during response to numerous events/exercises and the inherent development of *adapatability* on the part of the operations and support staff. An experienced staff with an in-depth understanding of the capabilties and limitations of the models and system can quickly develop procedures to apply working models to diverse problems such as power plant releases, explosive material disposal, falling satellites, and toxic gas accidents. ARAC can improve the expertise of site personnel by providing training and by participating in local exercises. ARAC assessors are well trained in emergency response, experienced in dealing with on-site authorities, and quick to catch and question errors (e.g., mistaken release coordinates and mixups in standard vs daylight time).

Information Consistency

Finally, but of no less value, is the *information consistency* provided by a centralized service. The benefit or virtue of consistency is that the information presented to authorities at local, regional, state, and federal/national levels always derives from similar validated models, incorporates nationally accepted dose-conversion factors, appears in the same graphical form (layouts, units, labeling, etc.), and highlights the same dose thresholds. For authorities concerned with multiple sites, this consistency eliminates the startup learning problem associated with each event and provides a reference system that allows rapid relative scaling of event magnitude. This aspect could save valuable time for decision-makers in the critical early phase of emergencies.

Summary

Complex dispersion models can be used effectively for real-time radiological emergency response if adequate consideration is given to optimizing the quality of the input data and resulting projections, minimizing the calculation and delivery time, and decreasing the system's vulnerability to hardware and software failures. Because of the high costs associated with developing such a sophisticated capability, the system is most cost-effective when used for centralized emergency response. The more sites to be supported, the more probable it is that a high level of emergency response capability can be achieved in a cost-effective manner. Aside from the economics associated with this centralized capability, there is the value of having an objective, trained staff that can produce quality projections, a service that is available for off-site accidents, expertise that can only be gained through experience, and projections that are consistently presented.

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